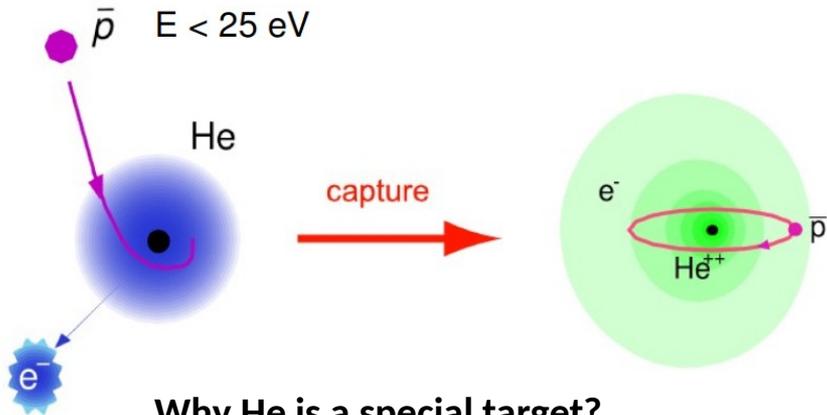




**Workshop on Light Anti-Nuclei as a Probe for New Physics  
Lorentz Center – Leiden (NL)**

**Francesco Nozzoli INFN-TIFPA (Trento)**

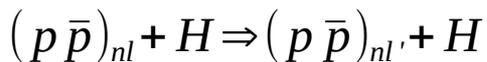
# a possible “new” signature: He metastable states



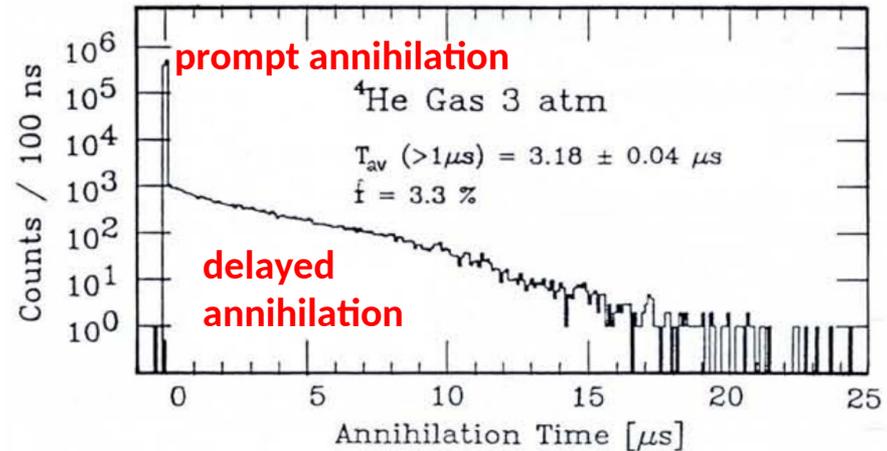
Why He is a special target?

1) the Auger decay is suppressed as well due to large level spacing of the remaining electron ( $\sim 25$  eV) compared to the small ( $\sim 2$  eV)  $n \rightarrow n-1$  level spacing of  $\bar{p}$   
 $\Rightarrow$  metastability is unexpected and excluded for  $Z > 3$  atoms (metastability for  $\text{Li}^+$  target?  $\rightarrow$  still not confirmed by expt.)

2) the remaining electron in  $\bar{p}\text{He}$  suppresses the collisional Stark effect (the main de-excitation channel for  $p\bar{p}$  system)



-In matter lifetime of stopped  $\bar{p}$  is  $\sim$ ps  
 -In liquid/gas He delayed annihilation: few  $\mu\text{s}$  ( $\sim 3\%$  of the  $\bar{p}$ ) (discovered @ KEK in 1991)  
 The electron is on 1s ground state, while the  $\bar{p}$  (or also  $\pi, k, \bar{d}$ ) occupies a **large n** level ( $\sim 38$  for  $\bar{p}$ ) ( $\sim$ same bounding energy of the ejected  $e^-$ )  
 Theory: Phys. Lett. 9 (1964) 65 PRL 23 (1969) 63

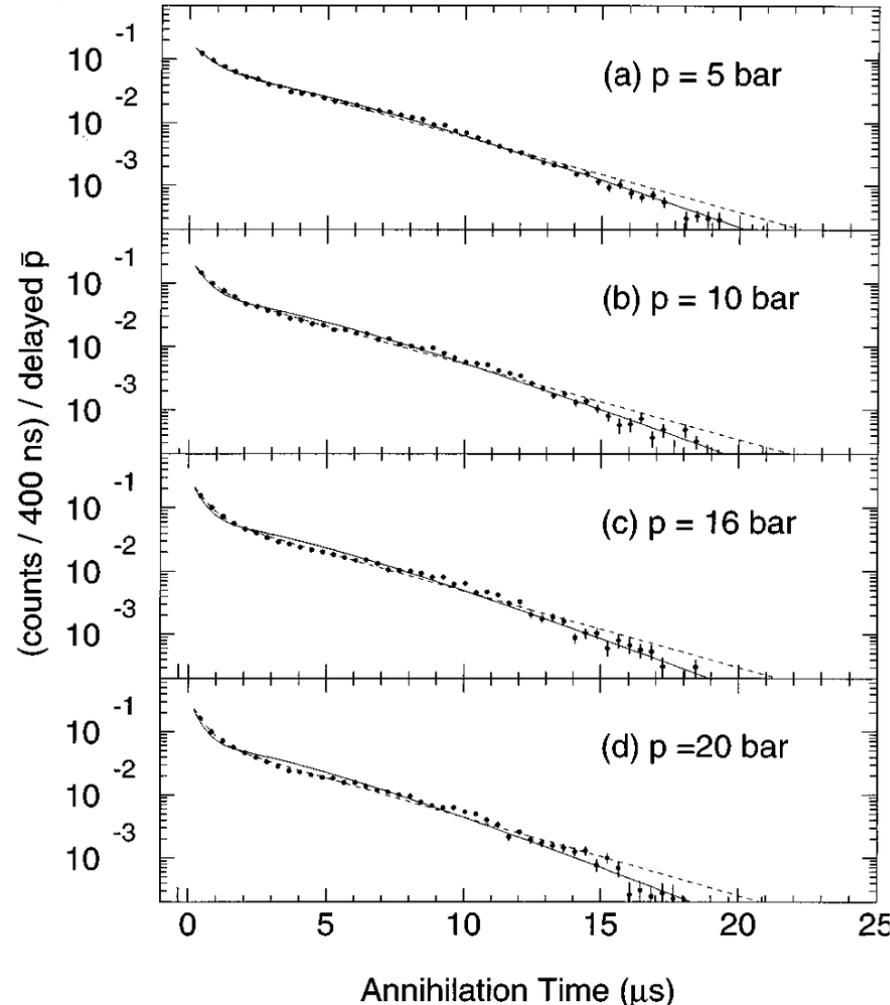


a signature for  $Z=-1$  antimatter capture in He is a  $\sim \mu\text{s}$  delayed energy release (in  $\sim 3\%$  of cases)

Not really new: similar effect already proven, and used, by the ASACUSA experiment

# Lifetime & fraction vs pressure vs particle mass

Phys Rev A 53 (1996) 3129 He @ room Temperature



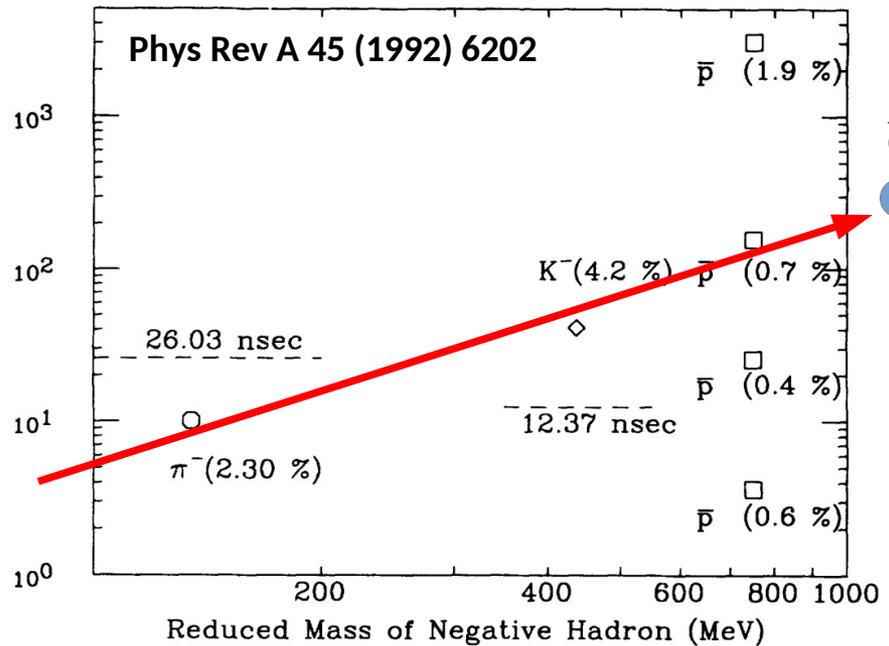
NOT a pure exponential:

Fast and Slow components

**Increasing Pressure → Fast component increase**

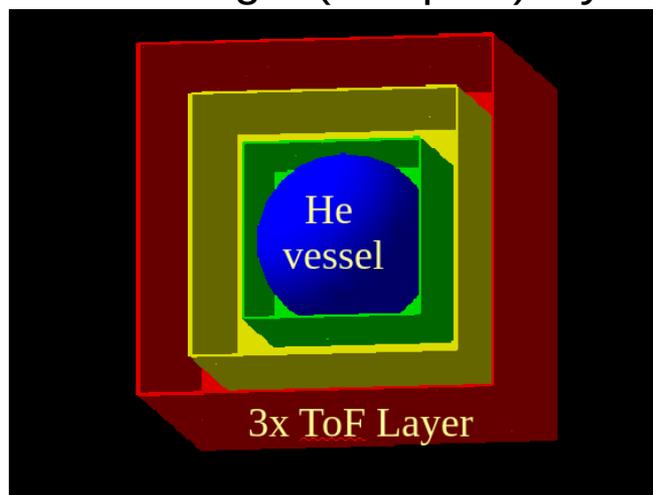
Isotope effect:

expected lifetime increase as squared of the reduced mass => **expected for antideuterium**

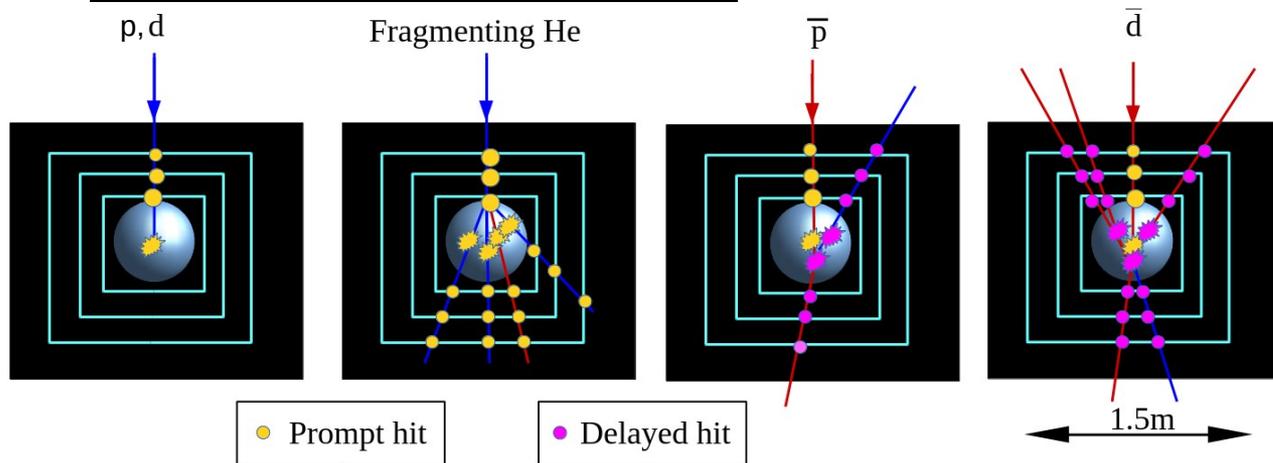


# Anti Deuteron He Detector (ADHD)

**Concept:** HeCalorimeter (scintillator)  
3xTime of Flight (compact) layers



Status: preliminary Geant4 simulation  
 Detector size: External ToF  $L = 1.5\text{m}$ ;  
 Vessel  $R=45\text{cm}$  Thick= $3\text{cm}$  “thermoplastic”  
 He pressure 400bar (typ. He bottle 130bar)  
 (“commercially” feasible space qualified)  
 Detector mass: He = 20 kg Vessel = 100kg  
 ToF = 110 kg ( 4mm scintillator thickness)  
 Kinetic energy range: 0.06-0.15 GeV/n  
 (threshold due to energy loss in vessel/ToF)



Particle identification by:

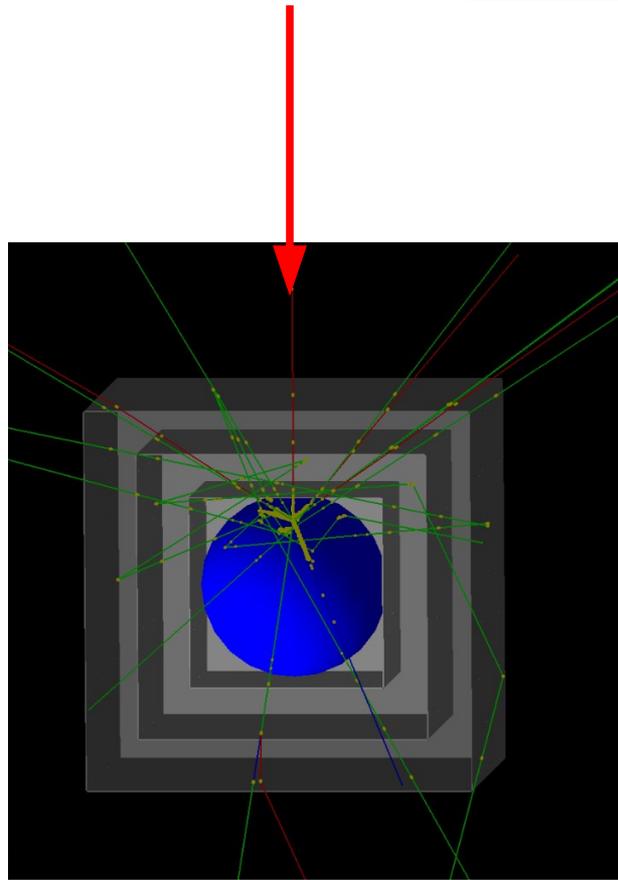
- 1) timing of tracks
- 2)  $dE/dx$  on ToF
- 3) Beta ToF
- 4) Prompt HeCal Energy
- 5) Delayed HeCal Energy
- 6) event topology

# GEANT4

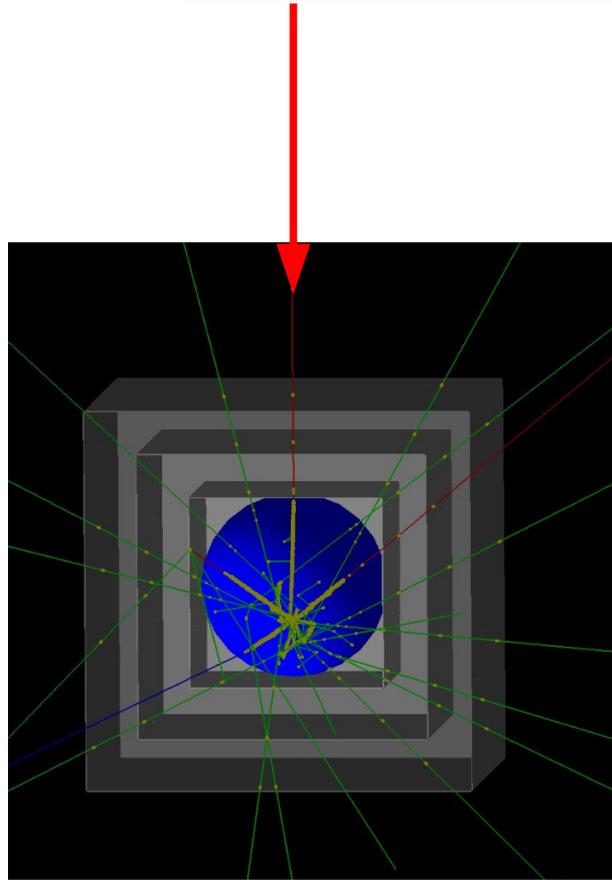
$\bar{d}$  (65MeV/n)

$\bar{p}$  (230MeV)

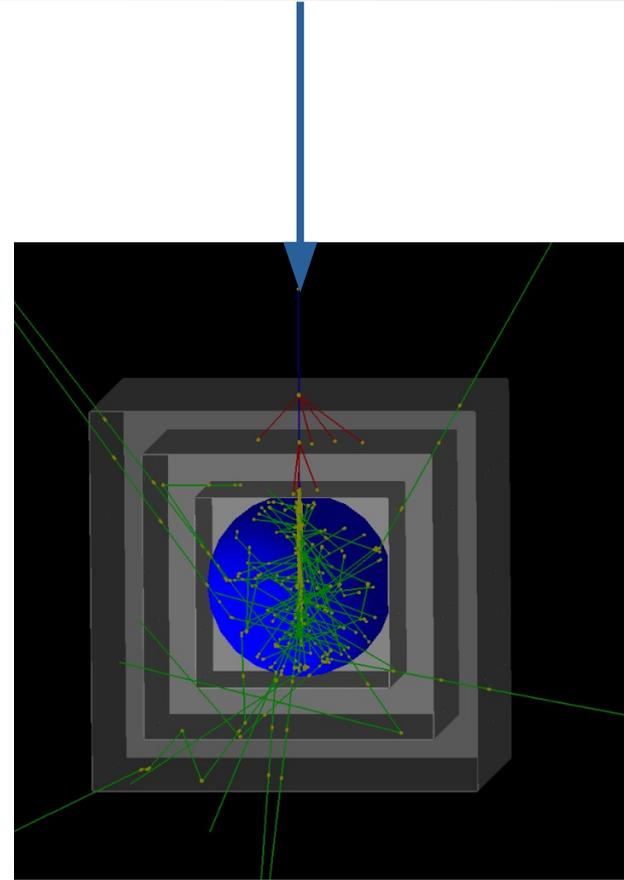
Carbon (600MeV/n)



4 charged outgoing  
(+ pair production)



3 charged outgoing



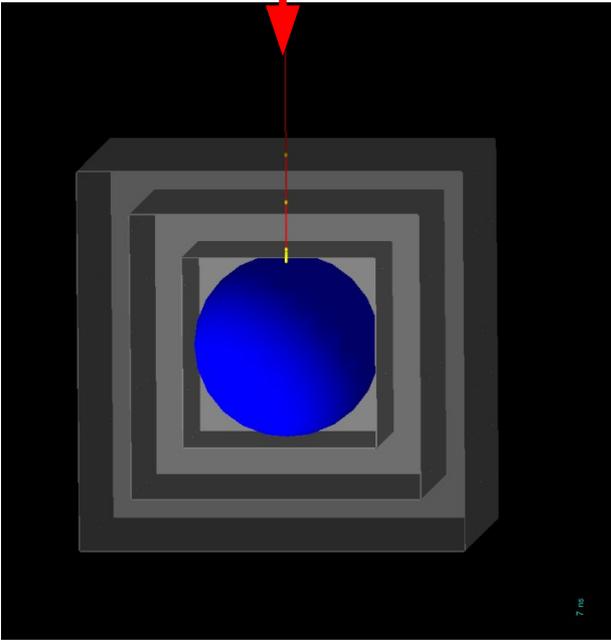
0 charged outgoing

Negative Positive Neutral charges

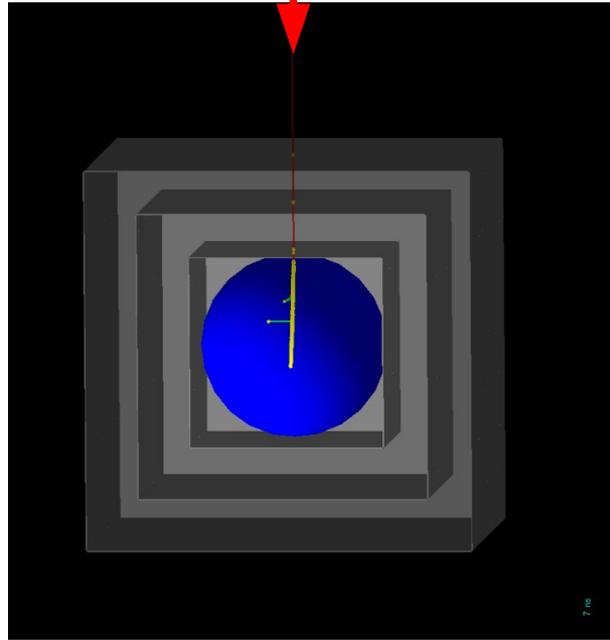
$\bar{d}$  (65MeV/n)

[0-7] ns  
 $\bar{p}$  (230MeV)

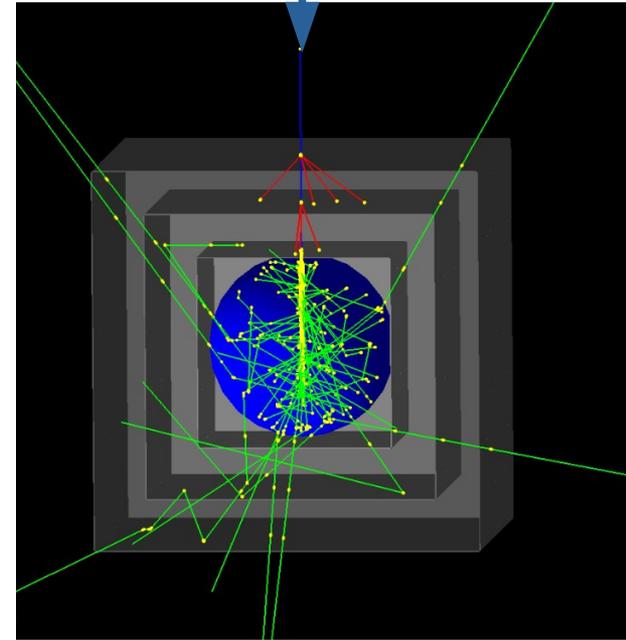
Carbon (600MeV/n)



... ok it is slow ...  
prompt HeCal signal  
3 hits in ToF



prompt HeCal signal  
3 hits in ToF

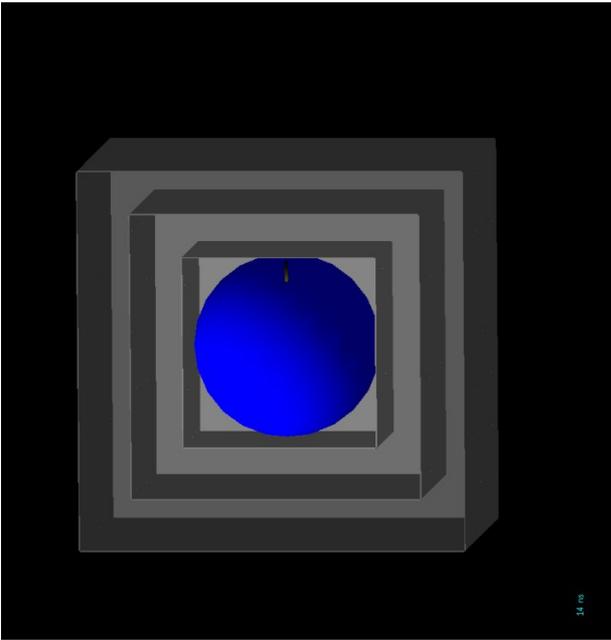


prompt HeCal signal  
10 hits in ToF

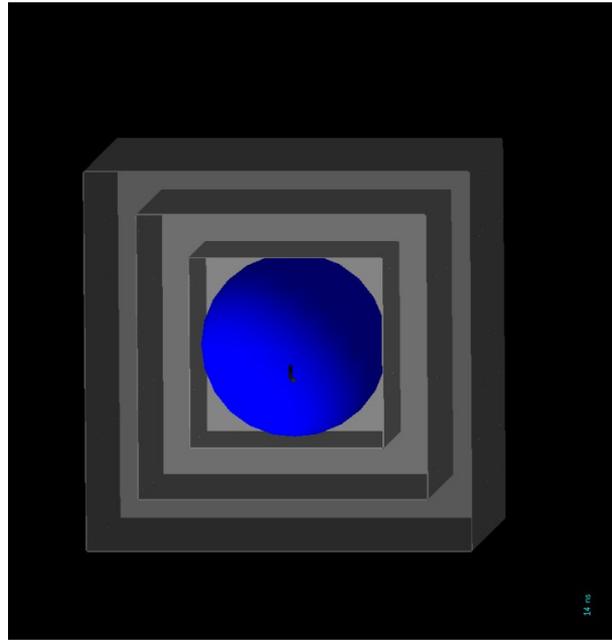
$\bar{d}$  (65MeV/n)

[7-14] ns  
 $\bar{p}$  (230MeV)

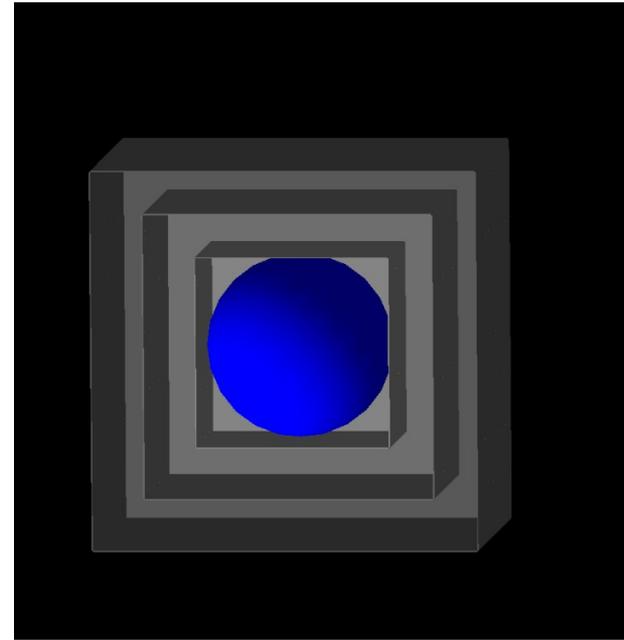
Carbon (600MeV/n)



stopped by HeCal  
small tail in prompt  
HeCal signal



stopped by HeCal  
small tail in prompt  
HeCal signal

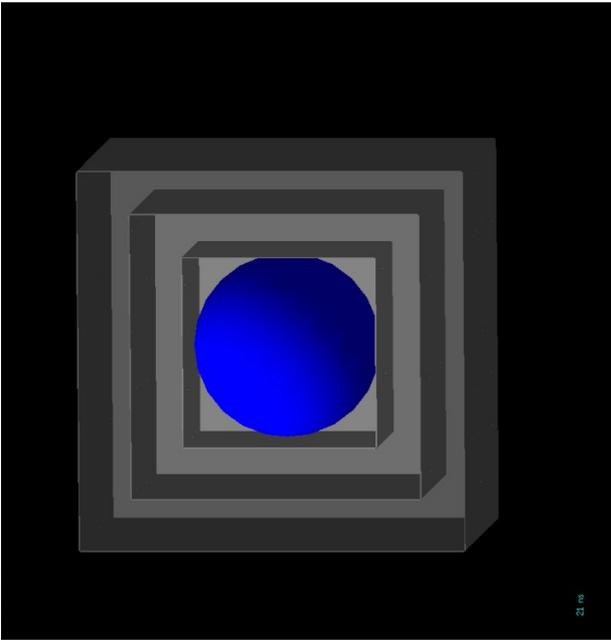


...nothing

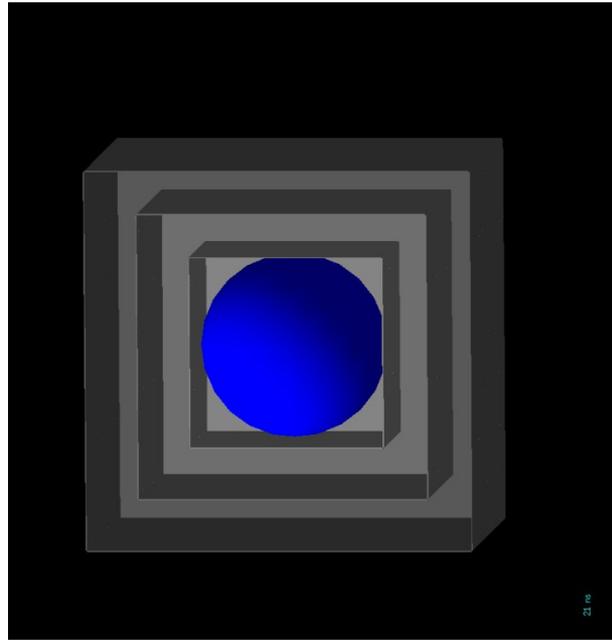
$\bar{d}$  (65MeV/n)

[14-60] ns  
 $\bar{p}$  (230MeV)

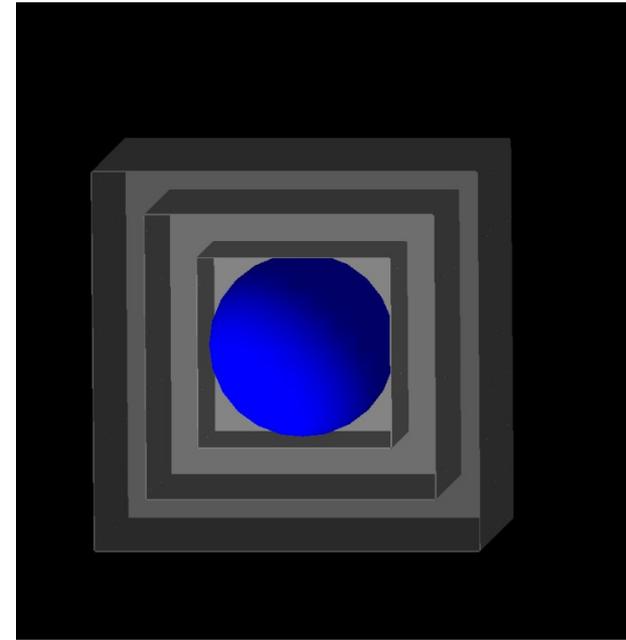
Carbon (600MeV/n)



Antideuteron orbiting He



Antiproton orbiting He

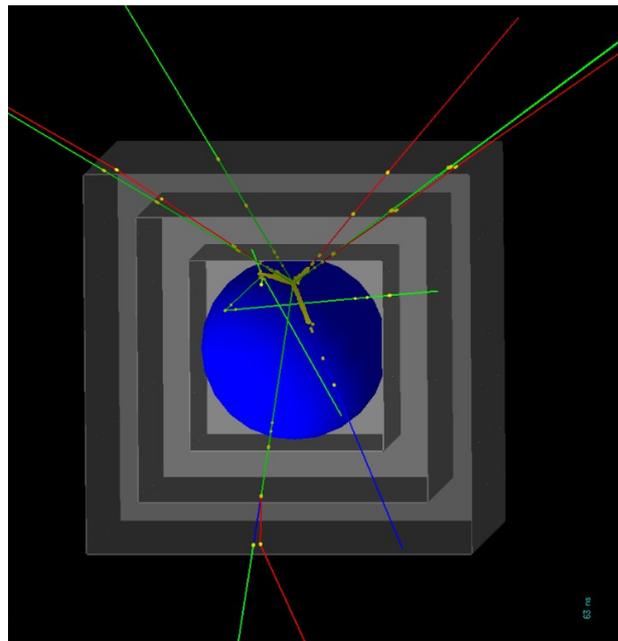


...nothing

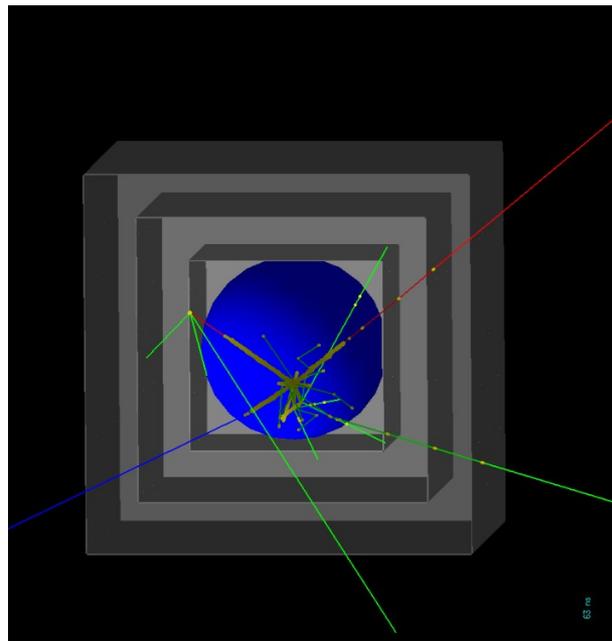
$\bar{d}$  (65MeV/n)

[60-70] ns  
 $\bar{p}$  (230MeV)

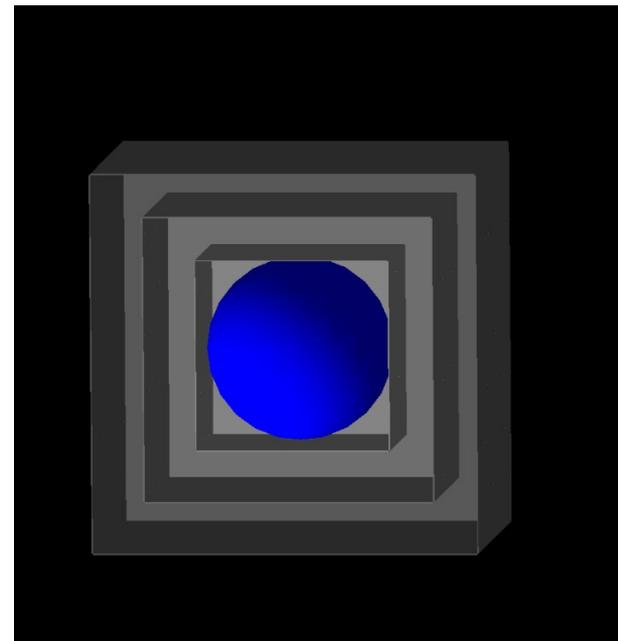
Carbon (600MeV/n)



Antideuteron annihilation



Antiproton annihilation

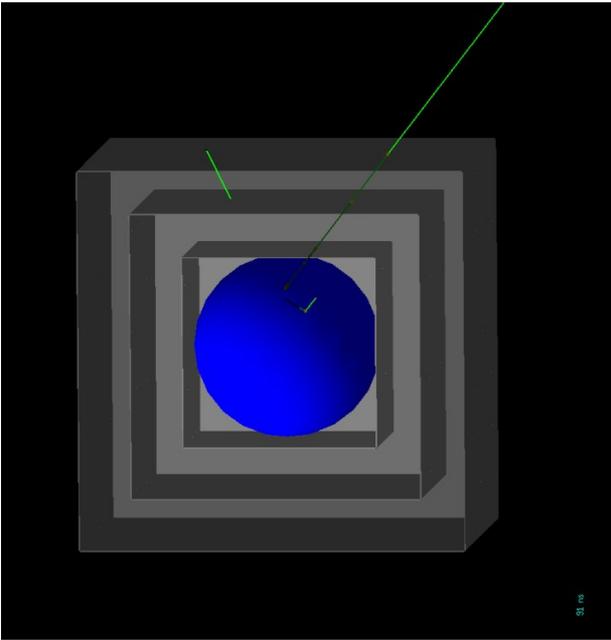


...nothing

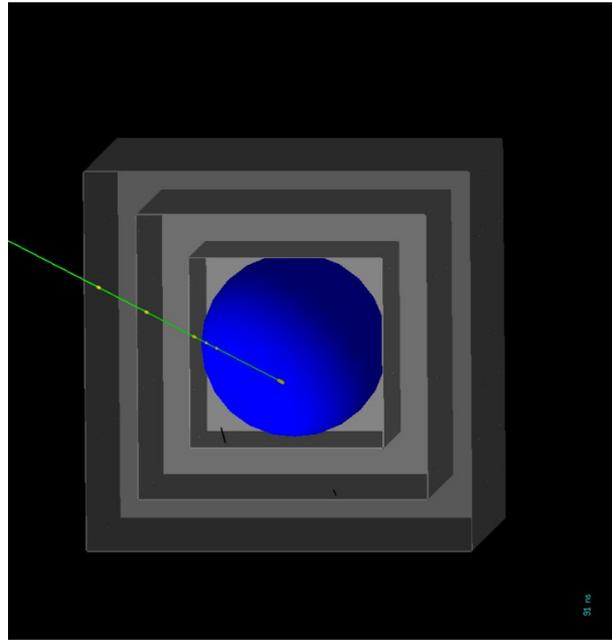
$\bar{d}$  (65MeV/n)

[70-XXX] ns  
 $\bar{p}$  (230MeV)

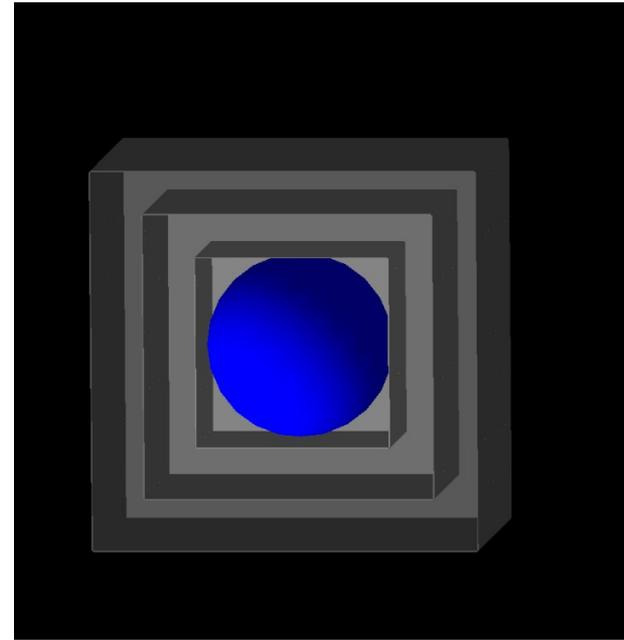
Carbon (600MeV/n)



small nuclear processes

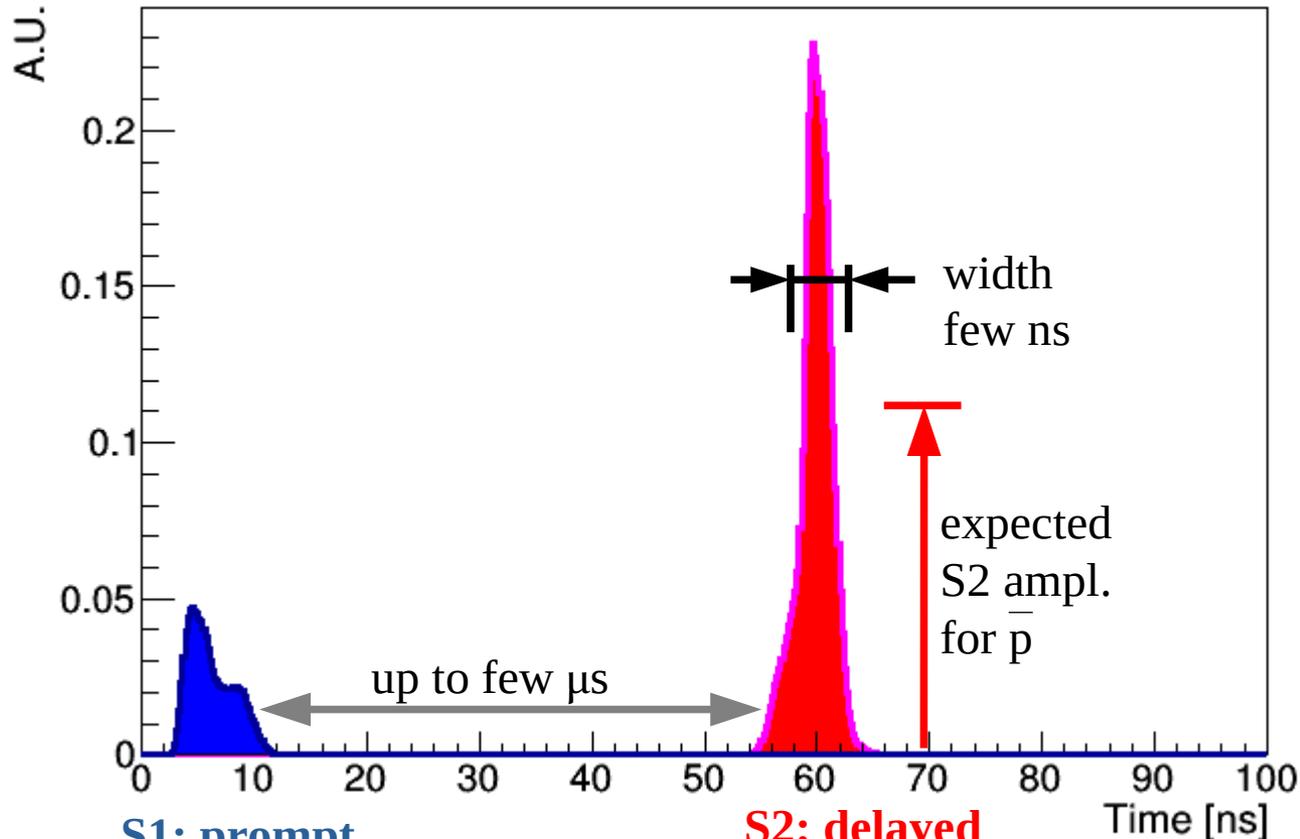


small nuclear processes



...nothing

# Typical HeCal signature for $\bar{p}$ and $\bar{d}$



**S1: prompt**

$\bar{p}$  or  $\bar{d}$

kinetic energy

(- energy loss)

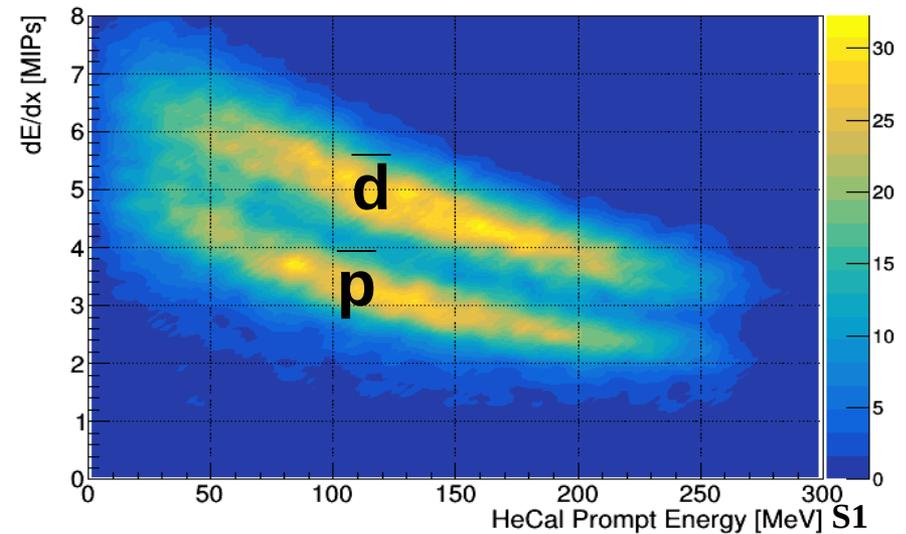
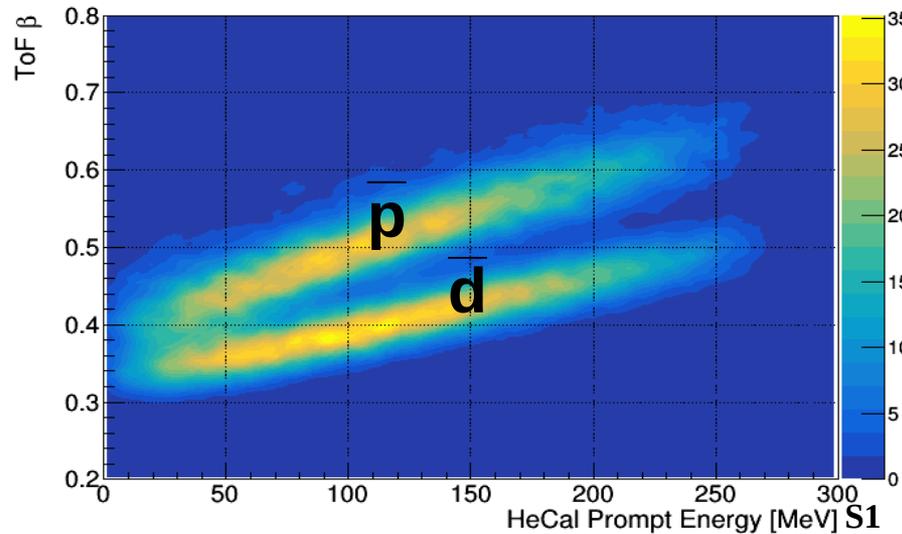
**S2: delayed**

Charged  $\pi/\mu$

Typ.  $S2 > S1$

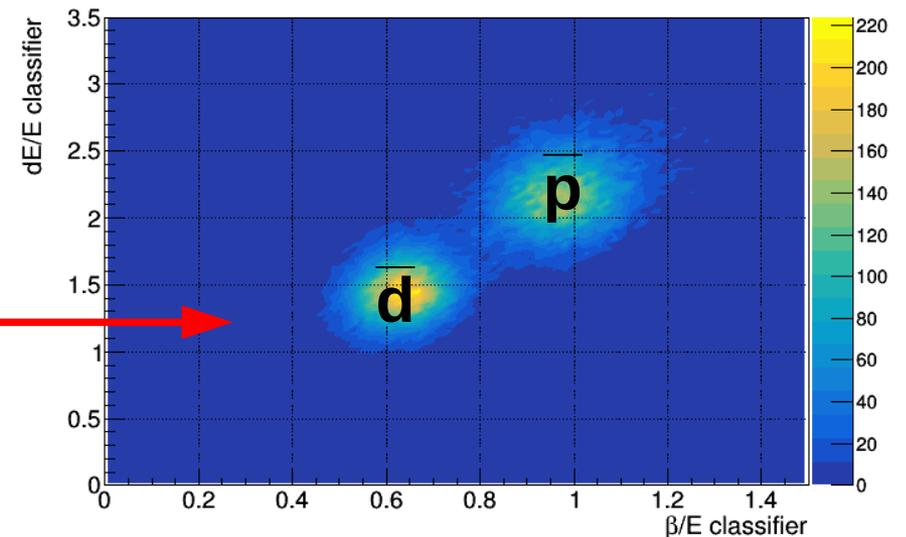
$S2$  independent by  $E_k$

# $\bar{p}/\bar{d}$ separation: prompt signal



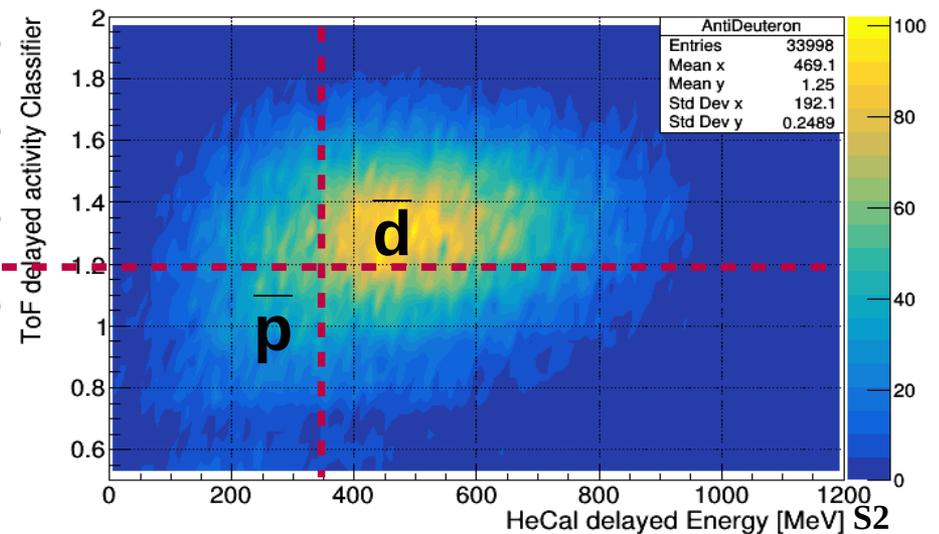
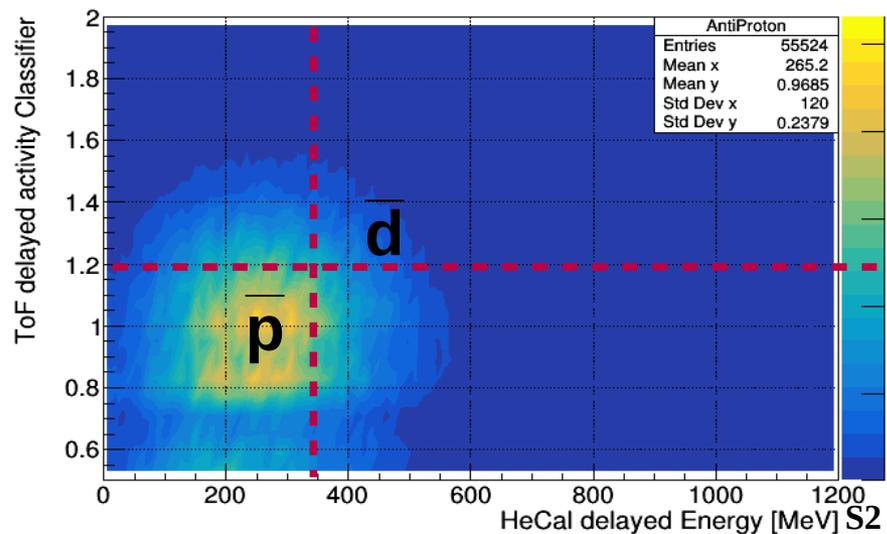
ToF goals (30cm baseline & 4mm thickness):  
 $\beta$  resolution 5%  $\Rightarrow \sigma_{x/y}$  ~few cm &  $\sigma_T < 0.1$  ns  
Energy resolution 10%

Parametrization of ( $\beta$  vs  $E$ ) & ( $dE/dx$  vs  $E$ )  
2 “independent” classifiers  $\longrightarrow$   
that can be combined to obtain an overall  
“Prompt signal classifier”



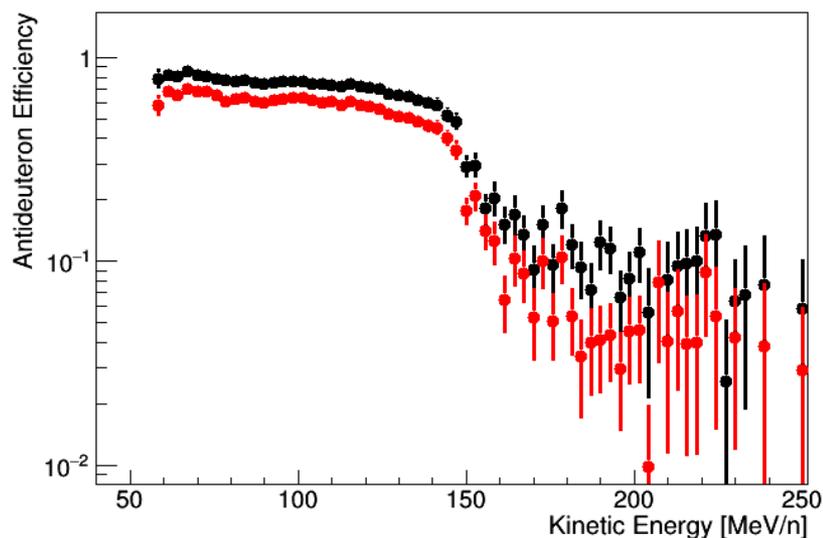
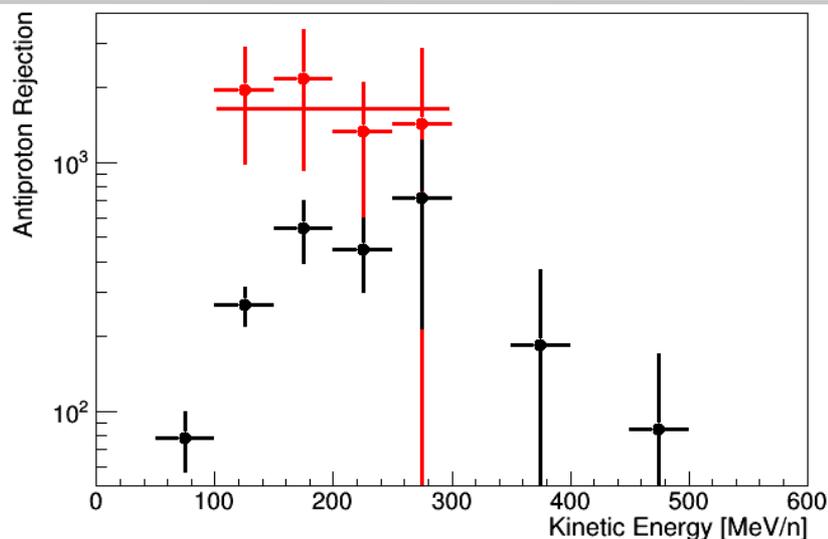
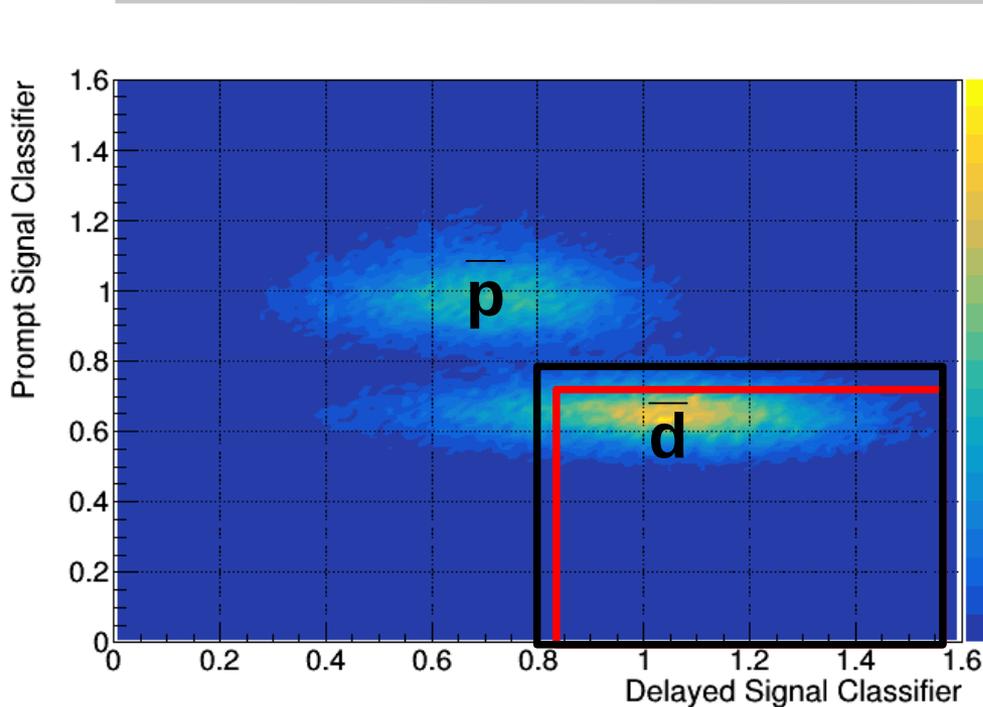
# $\bar{p}/\bar{d}$ separation: delayed signal

delayed signal amplitude is independent from  $E_{kin}$ :  $\sim 3$  charged pion/antinucleon  
-ToF delayed activity classifier = #ToF delayed hits  $\oplus$  ToF delayed energy  
(can be improved a bit with full track topology)



2 “independent” classifiers  
that can be combined to obtain an overall  
“Delayed signal classifier”

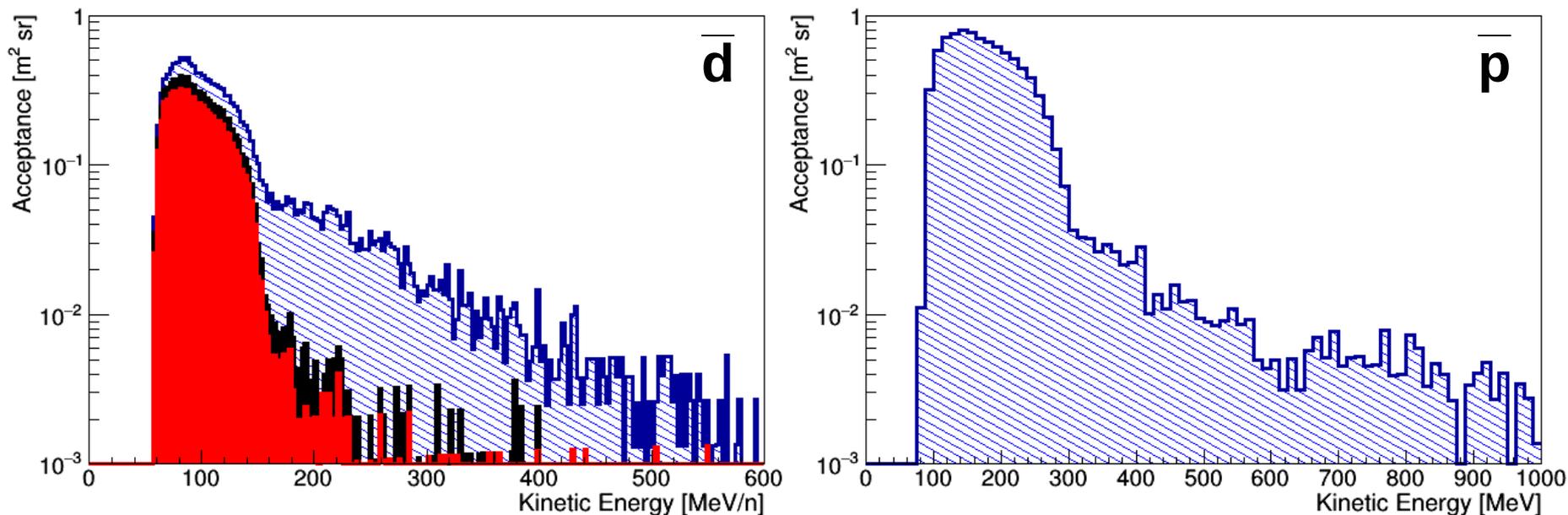
# $\bar{p}/\bar{d}$ separation



$\bar{p}$  rejection 1500 @ 65%  $\bar{d}$  efficiency  
=> possibility to detect  $1\bar{d}/1000\bar{p}$   
[50-150] MeV  $\bar{p}$  flux  $< 2-3 \times 10^{-3} (\text{m}^2\text{s sr GeV})^{-1}$   
Therefore with these ADHD performances  
the  $\bar{p}$  background is limiting the sensitivity to:  
 $\bar{d}$  flux  $> 2-3 \times 10^{-6} (\text{m}^2\text{s sr GeV/n})^{-1}$

# $\bar{p}/\bar{d}$ acceptances

Baseline: S1 & S2 & ( $dE/dx > \text{MIP}$ ) & 3 prompt ToF hits

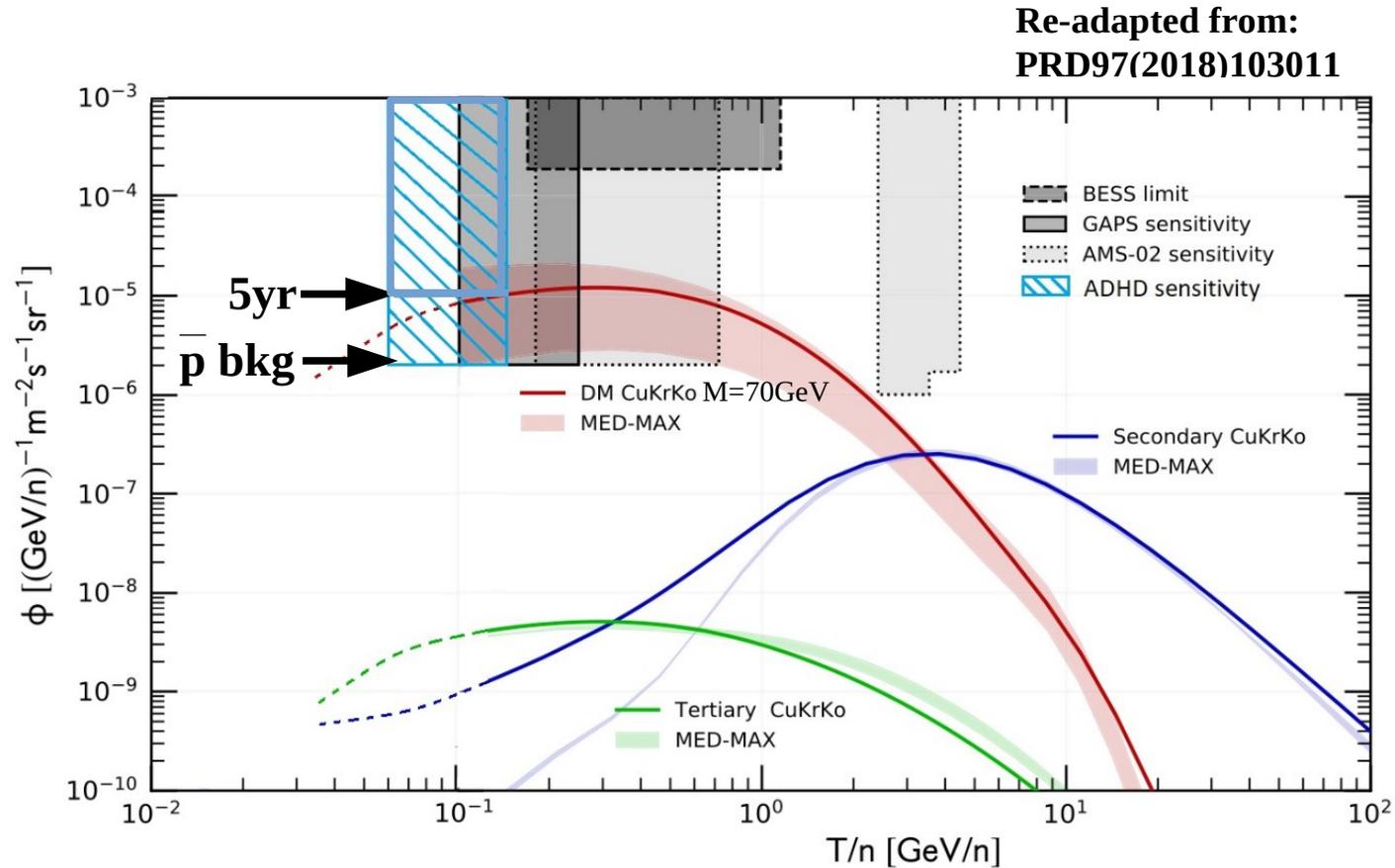


These have to be multiplied for the probability to form metastable states  $\sim 3.3\%$

Example of sensitivity/new measurements with 5yr data @  $0.2 \times 0.033 \text{ m}^2 \text{ sr}$ :

- Antideuteron [50-150]MeV/n:  $10^{-5} (\text{m}^2 \text{s sr GeV/n})^{-1}$  ( $< 0.3 \bar{p}$  background is expected)
- Antiproton: new measurement in 10 bins in the range [100-300] MeV with 5-10% error

# planned sensitivity



AMS02-GAPS-ADHD: different techniques, similar sensitivity, complementary Ek regions  
**Join of all the signatures in a future/ultimate Antideuteron detector?**

---

**ADHD**  
**technological readiness level**

# The He VESSEL

Vessel (&ToF) sets the energy window: [50-150] MeV/n

Wall thickness  $s$  x density (+ToF) => lower Energy threshold

Pressure  $P$  & radius  $R$  => upper Energy threshold

we need a light/thin vessel + high  $P$  + large  $R$  ...

... and safety: ADHD gas stored energy is the same as ~ 4kg TNT

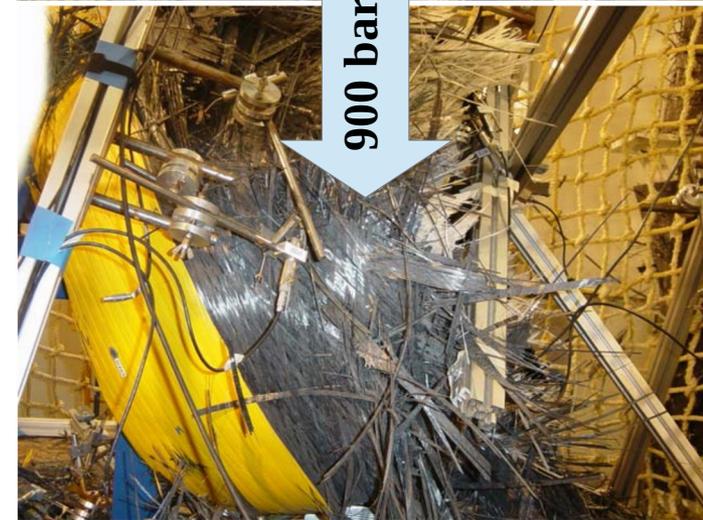
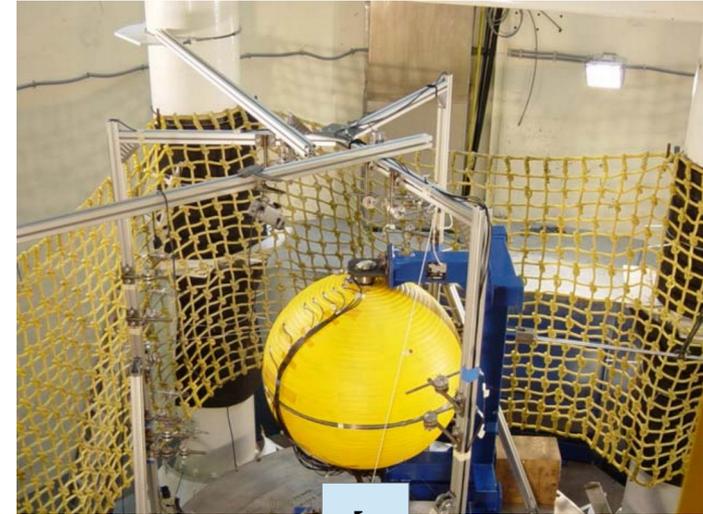
For cost reduction on the Ariane 5 launcher, EADS-ST intends to replace the usual and expensive titanium liner of He tank by a plastic one <http://www.dtic.mil/dtic/tr/fulltext/u2/a445482.pdf>



300L x 93kg  
Rin=41.7cm  
Rout=45cm  
density ~ 1.1g/cm<sup>3</sup>  
to be loaded with  
He @ 400 bar  
(safety factor 2.2)

spherical vessel  $P_{burst}$  prop.to  $R/s$

burst@900bar R=45cm s=3.3cm



# COPV for Hydrogen fuel is a commercial product

## Example: Faber in Italy



leader in the production of seamless steel and composite cylinders

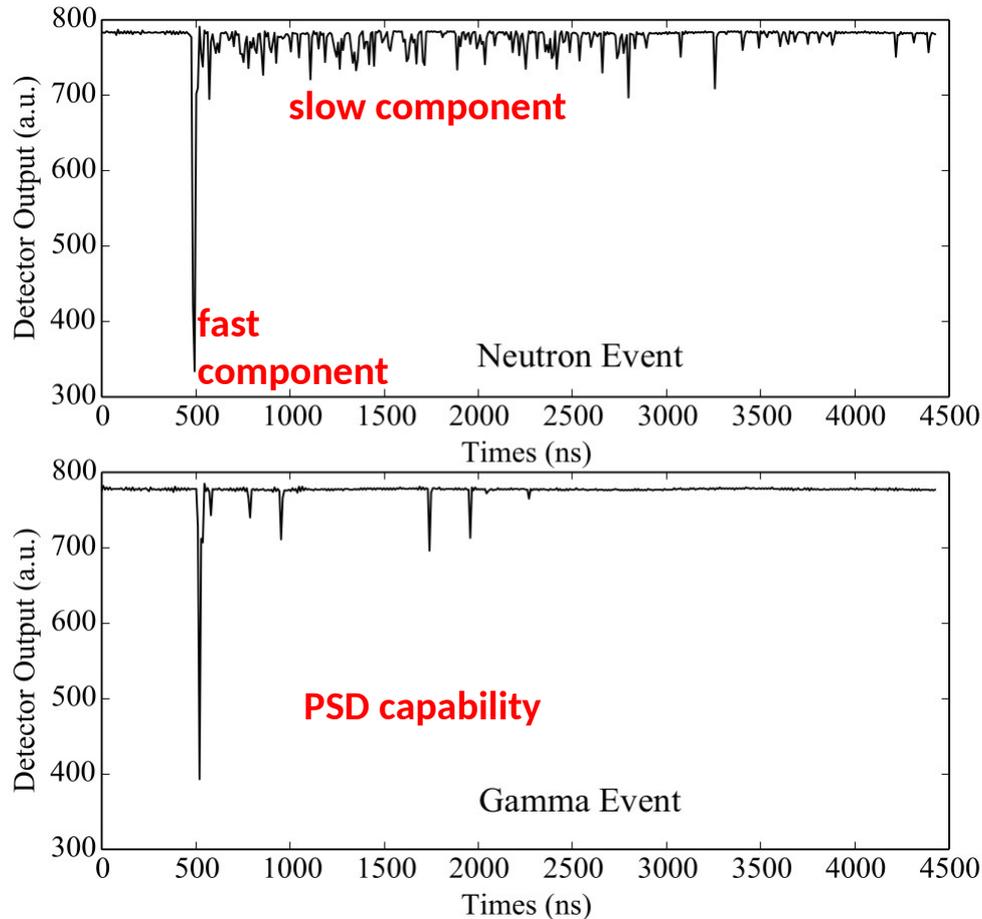
[HOME](#) [COMPANY](#) [TECHNOLOGY](#) [PRODUCTS](#) [QUALITY](#) [RESOURCES](#) [NEWS](#)



### Cylinders must be **light**

Faber relies on a unique +40 year track record which include a very comprehensive range of all Types of Cylinders (Type 1,2,3,4), eachone standing out for superior lightness, reliability and safety. The entire production process is controlled by Faber and performed in-house in one of our own dedicated plants. This ensures that Faber is capable of offering the right cylinder at a price that best fits the needs of our customers.

# The He Calorimeter



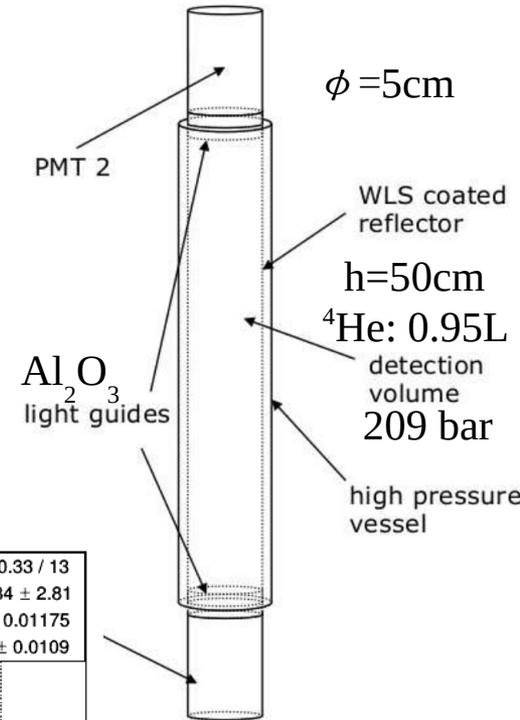
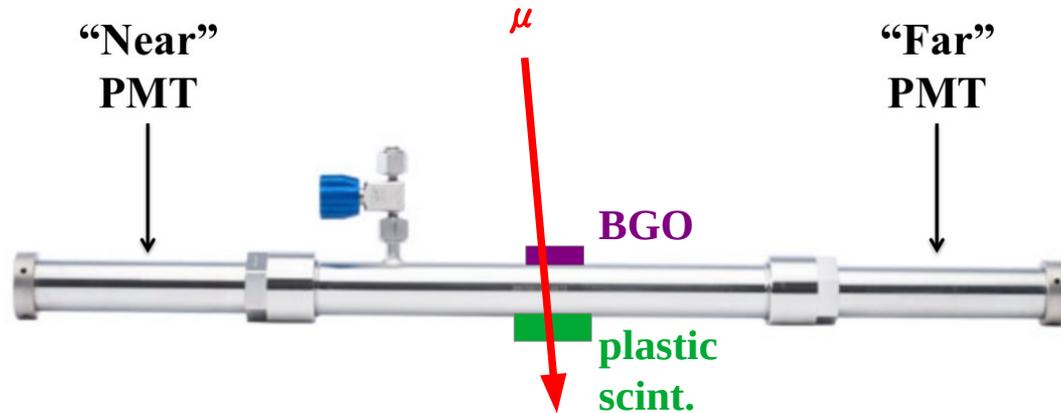
He as scintillator has a strong “fast” component (tens ns, 15000 ph/MeV)

He is scintillating in VUV:  
Vessel have to be PTFE coated with an organic phosphor that converted the wavelength of the scintillation light from 80 nm to 430 nm.

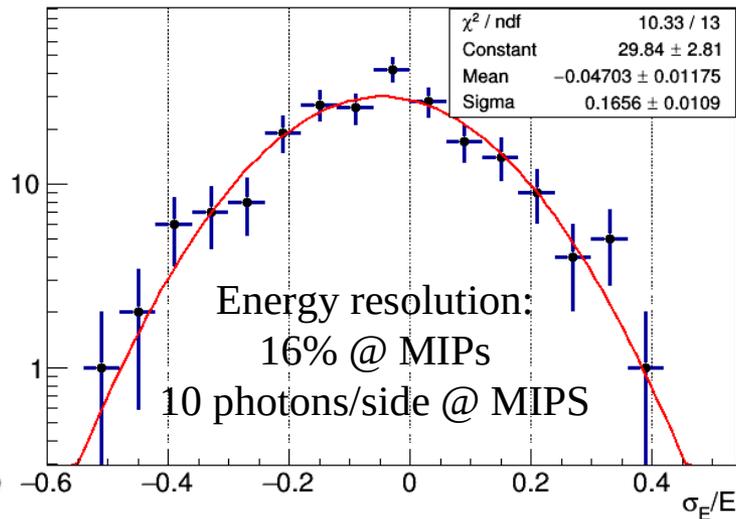
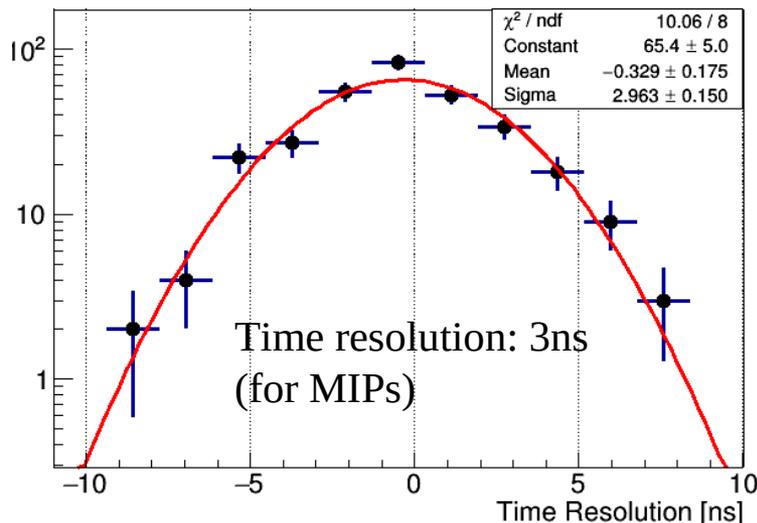
High pressure issue:  
Most probably PMT cannot be used inside the high pressure vessel => SiPM

(test for a possible use of SiPM in space and their radiation tolerance are currently ongoing @ TIFPA proton beam)

# HeCal prototype: ARKTIS B670 test with Muons @ TIFPA

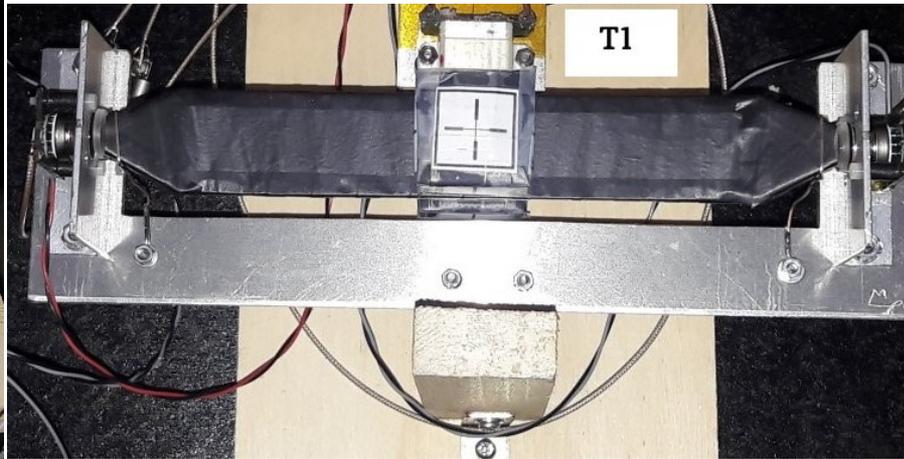
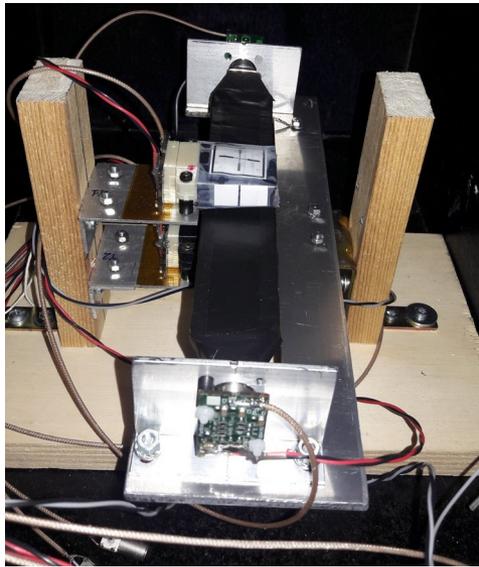


Good performances also for muon MIPs  
(30MeV-250MeV proton beam test in Trento scheduled for 03/2020)



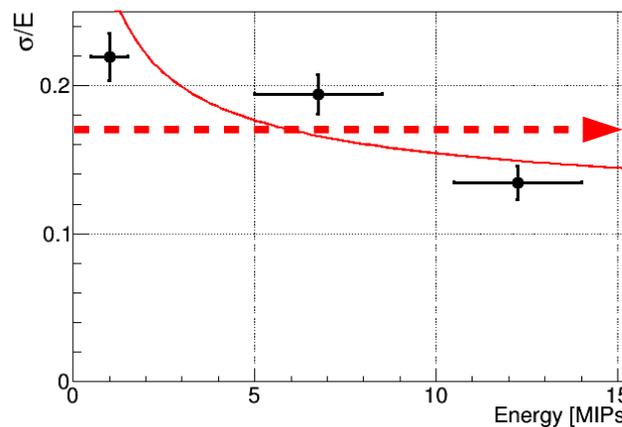
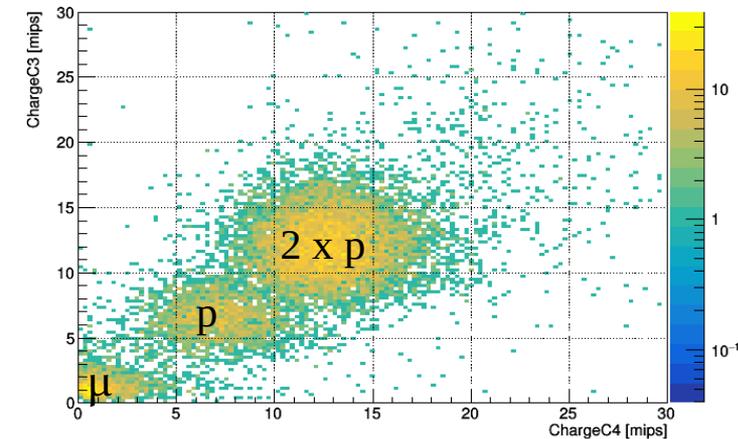
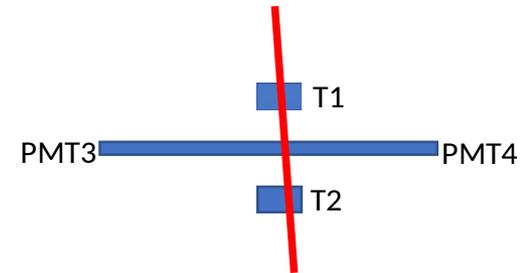
9cm of position resolution from signal amplitude asymmetry (for MIPs)

# Test of a ToF bar: Energy resolution



Test of a **very thin** ToF bar:  
 15cm x 3cm x 2mm EJ-200  
 2 x Hamamatsu R9880-210

- proton beam  $E = 62 \text{ MeV}$
- muons (cosmic) (MIPs)

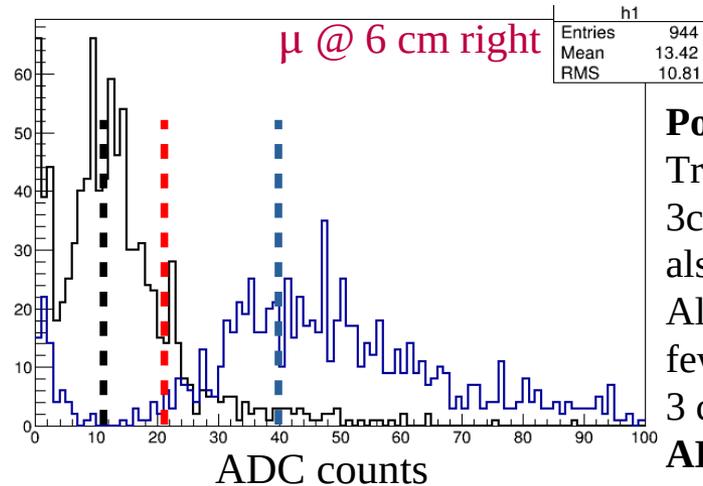
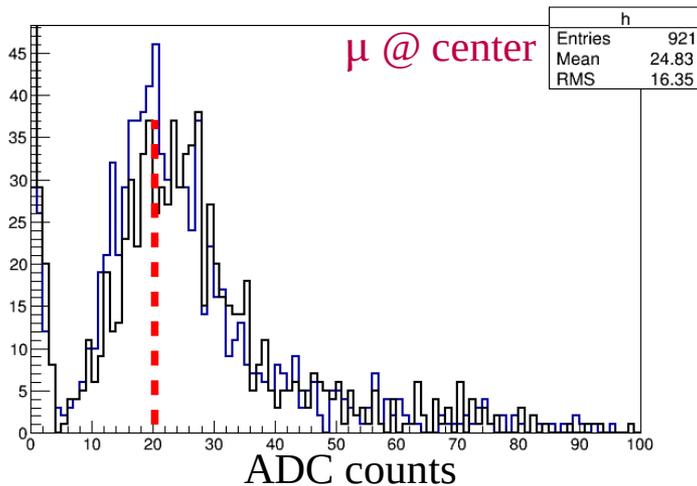
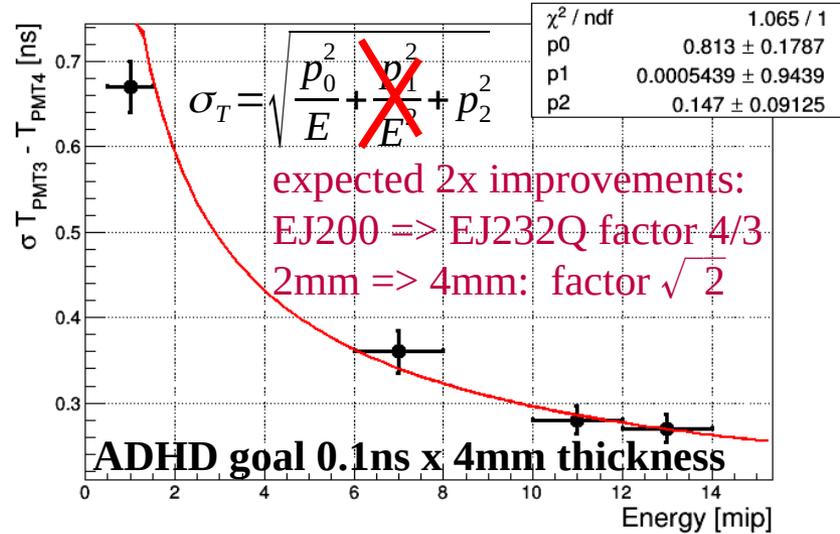
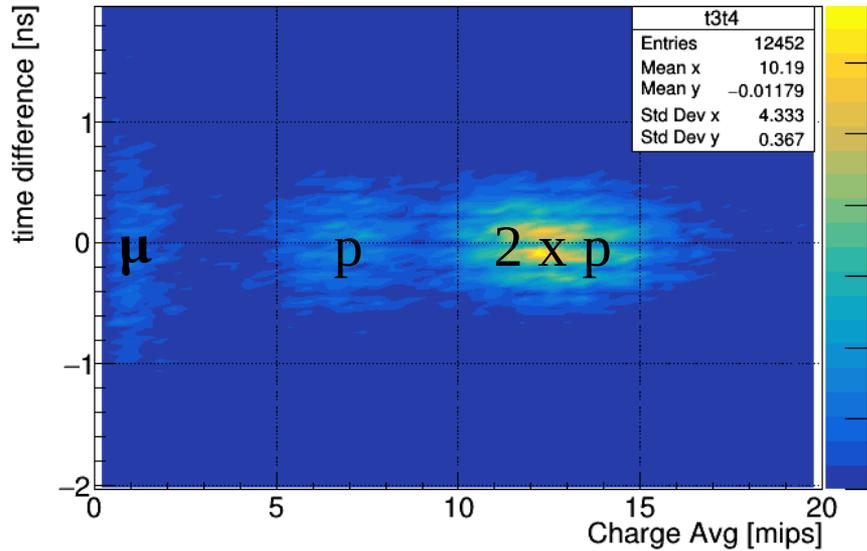


**ADHD goal already fulfilled**

10% Energy resolution in MC simulation using 3layer of 4mm each (test with 2mm).  
 (17% = 10%  $\sqrt{3}$ )

=> **reasonable to reach 5%**  
 number of readout channel  
 problem:  $L \times 5\text{cm} \Rightarrow 900 \text{ ch}$   
 $3 \text{ cm} \times 15 \text{ cm} \sim 12000 \text{ ch}$

# Test of a ToF bar: Space/Time resolution



**Position resolutions @ %:**  
 Transverse to the bar:  
 $3\text{cm}/\sqrt{12} \sim 1\text{cm}$   
 also 5cm bar width is enough  
 Along the bar:  
 few cm from side amplitudes  
 3 cm from timing (0.1ns res)  
**ADHD goal already fulfilled**

## Conclusion / to do list

---

ADHD is a new technique for Antideuteron identification in He target:

Result of  $\bar{d}$  and  $\bar{p}$  MC simulations (0.1ns x few cm ToF resolution):

- Antiproton in Antideuteron region  $\sim 1/1500$  @ 65%  $\bar{d}$  efficiency
- Feasible acceptance  $\sim 0.2\text{m}^2\text{sr}$ , 20kgHe @ 400Bar, 27m<sup>2</sup> of ToF
- $\bar{d}$  sensitivity 5y [50-150]MeV/n:  $10^{-5} (\text{m}^2\text{s sr GeV/n})^{-1}$  ( $<0.3$   $\bar{p}$  background is expected)
- $\bar{p}$  in 5y, new measurement in 10 bins in the range [100-300] MeV with 5 - 10% error
- Test of HeCal with cosmic muons: DONE 3ns time resolution 16% energy resolution @ MIP

To do list/wishlist:

- Evaluate Proton and other Cosmic Ray pile-up background (and sensitivity): ongoing
- Test of a detector prototype based on ARKTIS B670 200Bar He scintillator:
  - proton beam test in Trento [50-230] MeV: scheduled in 2020
  - test to  $\bar{p}$  beam: few year in the future, after prototype optimization (test also Li target)
- SiPM qualification for space and rad-tolerance: ongoing @ Trento proton beam
- ToF 0.1ns resolution: still to be proven (now  $\sim 0.3\text{ns}$  is obtained, 0.15ns as AMS-02 is feasible)
- How to manage  $\sim 1\text{k}$  to  $10\text{k}$  ToF channels: still to be proven (AMS-02 ToF+ACC use 100ch)

**ADHD:** Attention Deficit: maybe ... **H**yperactivity **D**isorder: guaranteed!

---